Introduction to Masonry Design

Richard Bennett, PhD, PE
The University of Tennessee

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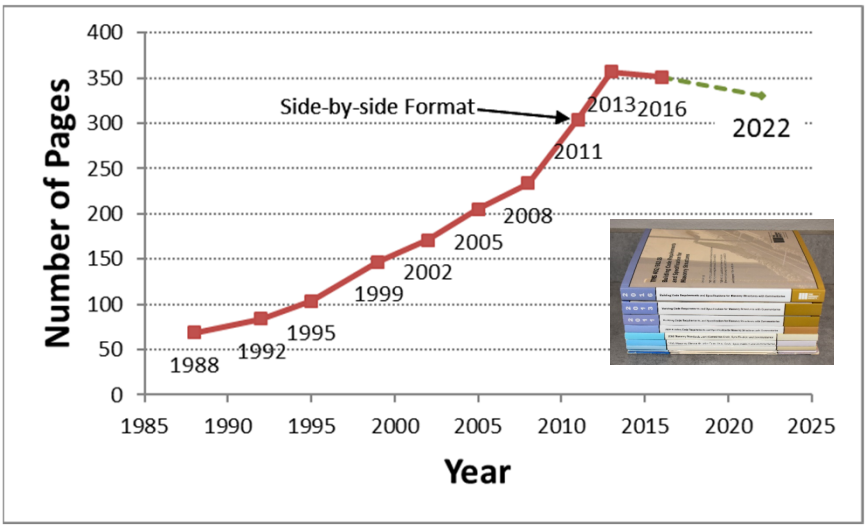
TMS 402/602 Code



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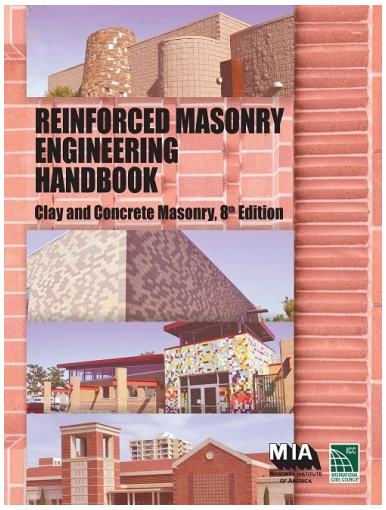
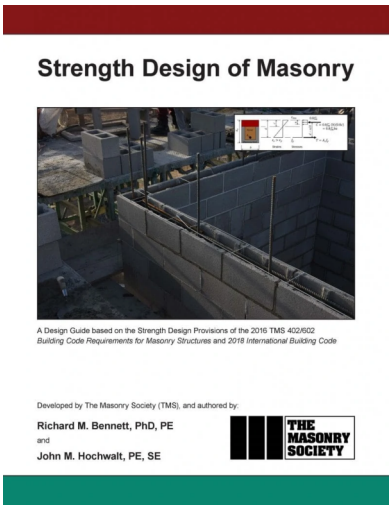
Textbooks





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Masonry Organizations

Organization	Web Address	Comments
Brick Industry Association	www.bia.org	Technical Notes on Brick Construction
International Masonry Institute	ww.imiweb.org	Masonry Bibliography, 1830-1990
Masonry Institute of America	www.masonryinstitute.org	Reinforced Masonry Engineering Handbook
National Concrete Masonry Association	www.ncma.org	Manual of Facts on Concrete Masonry; e-TEK notes
The Masonry Society	www.masonrysociety.org	Masonry Society Journal; Designer's Guide; Database
Portland Cement Association	www.portcement.org	Concrete Masonry Handbook
Western States Clay Products Association	www.brick-wscpa.org	Technical Publications on Veneer and Structural Brick

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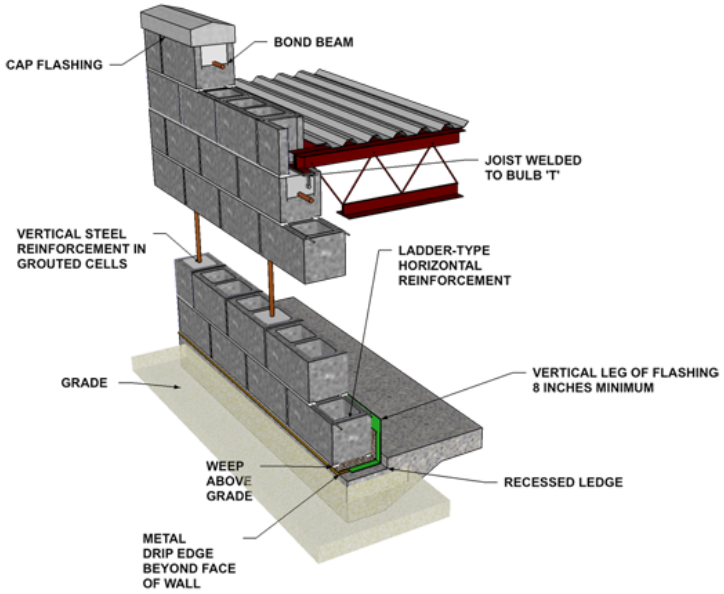
Reinforced Masonry Wall



http://www.masonrysystems.org/wall-systems/cavity-wall-concrete-block-veneer-reinforced-concrete-block/

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Other Notes and Spreadsheets

Introduction to Masonry Design

- Seminar Notes
  - Introduction to Masonry Design
- Excel Files
  - Reinforced Beam Analysis and Design
  - Interation Diagram: Partial Grout Out-of-Plane
  - Slender Wall Design
  - Interaction Diagram: Pilaster
  - Interation Diagram: Shear Wall
  - Splice Length
  - Anchor Bolt Design
- Detailed Notes (not covered during seminar)
  - Clay Masonry
  - Concrete Masonry
  - Mortar and Grout
  - Prism Strength, Reinforcement, Construction Practices
  - Masonry properties
  - Flexure Design: Non-bearing walls and lintels
  - Axial and Flexure: Bearing walls, pilasters, columns
  - Shear Walls, including special reinforced walls
  - Anchor Bolts
  - Allowable Stress Design

https://efcms.engr.utk.edu/ce576-2021-06/utah/

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Outline

1. Masonry materials
   A. Units
   B. Mortar
   C. Grout
   D. Prism strength
2. Flexure design
   A. Comparison to ACI 318
   B. Beams and lintels
   C. Non-bearing walls
3. Combined bending and axial loads
   A. Bearing walls
   B. Second-order effects
4. Shear walls
   A. Flexural strength (interaction diagrams)
   B. Shear strength (masonry and reinforcement)
   C. Special reinforced shear wall seismic requirements

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Units





https://www.constructionspecifier.com/durable-waterproofing-for-concrete-masonry-walls-redundancy-required/

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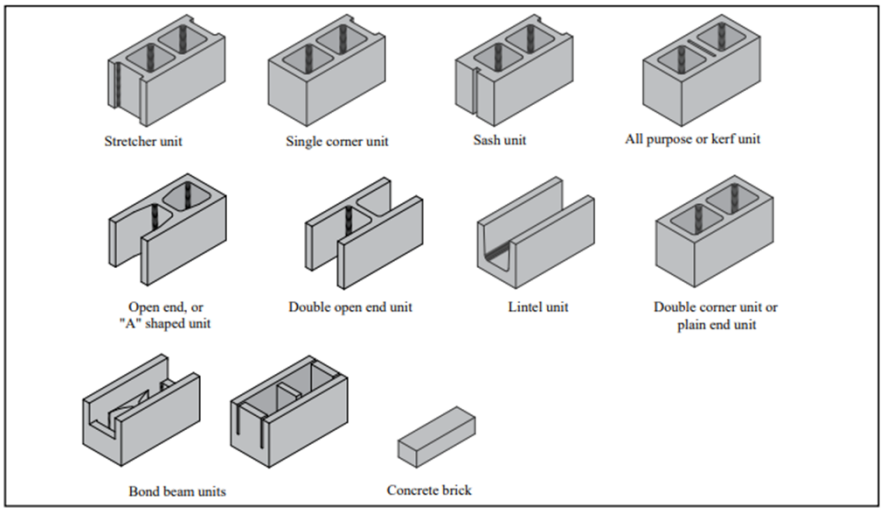
Concrete Block Shapes



https://ncma.org/resource/typical-sizes-and-shapes-of-concrete-masonry-units/

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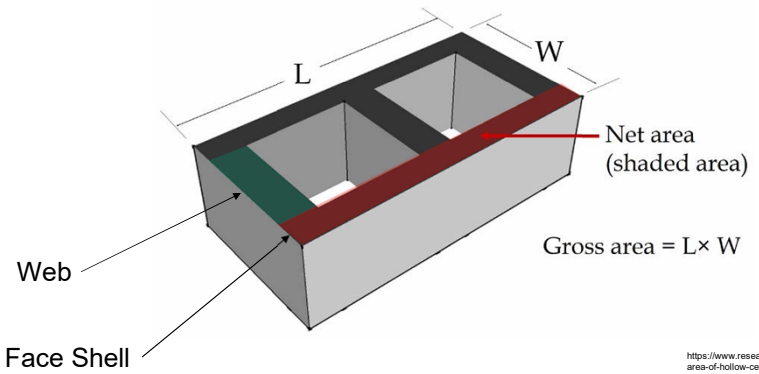
Concrete Masonry Strength

<u>Minimum Compressive Strength of CMU, net area</u>

2000 psi (average of 3); 1700 psi (individual)



https://www.researchgate.net/figure/Gross-and-net-area-of-hollow-cement-block_fig2_271508259

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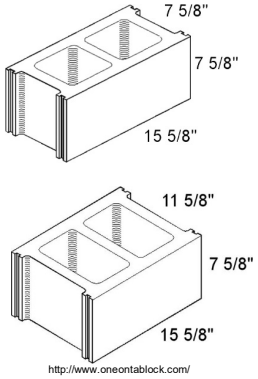
Unit Dimensions

Nominal size: **8** x **8** x **16** unit
width x height x length

Actual size:
7⅝ x **7⅝** x **15⅝** inch

Most units are 8 in. high and 16 in. long
Block is then referred to by thickness
12 in. block is $11^{5}/_{8}$ in. thick

Nominal Width of Unit (in)	Minimum Face Shell Thickness (in)
3 and 4	3/4
6	1
8	1 1/4
10	1 1/4
12	1 1/4



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Wall Weights (psf)

Grout Spacing	Wall Thickness (inch)					
	8	12	8	12	8	12
	105 pcf units		125 pcf units		135 pcf units	
No grout	31	43	36	50	39	54
48 in. o.c.	38	55	44	62	47	66
40 in. o.c.	40	57	45	65	48	69
32 in. o.c.	42	61	47	68	50	72
24 in. o.c.	46	67	51	75	54	78
16 in. o.c.	53	79	59	87	61	90
Full Grout	75	115	81	123	83	127

Wall weights from ASCE 7
NCMA TEK 13-B has slightly different wall weights

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Mortar





Mortar Types

M a **S** o **N** w **O** r **K**

strongest weakest

Typical uses:

- Type S: Structural masonry
- Type N: Non-structural masonry
- Type O: Tuckpointing

Kinds of Mortars



Portland Cement – Hydrated Lime:

- a combination of cement and lime



Masonry Cement

- Proprietary product
- Simple batching and "fluffiness" due to entrained air leads to good productivity.
- Codes restrict use in high seismic areas.



Mortar Cement

- Proprietary product similar to masonry cement
- More stringent requirements
- Recognized by codes to be equivalent to PCL mortar.

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Specifying Mortar

- Proportion Specification
  - Recipe for making mortar
  - Proportion specification governs if neither is given
- Property Specification
  - Property specification is for laboratory made mortar, not field mortar
  - Recipe developed based on lab mortar
  - Recipe used for field mortar
- No requirements for strength of field mortar
  - Strength of mortar has almost no effect on wall strength
  - Better test is mortar aggregate ratio



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Proportion Specifications

Mortar Type	Proportion by Volume (Cementitious Materials)		Aggregate Ratio (measured in damp, loose conditions)
	Portland Cement	Lime	
M	1	¼	2¼ to 3 times the sum of volumes of cementitious materials
S	1	over ¼ to ½	
N	1	over ½ to 1¼	
Masonry or Mortar Cement	1 part		

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Placing Mortar and Units





TMS 602 3.3.B

- Face shell bedding
- Cross webs mortared at base and grouted cells

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Grout





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Grout

- High-slump concrete (8-11 in.)
- Small size aggregate
- Bonds reinforcement to the masonry



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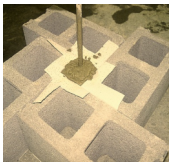
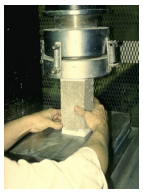
Grout Properties

Compressive Strength:

- 2000 psi
  - or prism compressive strength
- Average strength is about 4000 psi.


Prism Compressive Strength



Prism Compressive Strength

Compliance of f'_m is verified by either:

A. Unit strength method: TMS 602 Table 1 and Table 2

B. Prism testing (ASTM C1314)

f'_m (psi)	Net area compressive strength of clay units (psi)	
	Type M or S mortar	Type N mortar
1,000	1,700	2,100
1,500	3,350	4,150
2,000	4,950	6,200
2,500	6,600	8,250
3,000	8,250	10,300
3,500	9,900	----
4,000	11,500	----

Type M or S mortar: $f'_m = 500 + 0.3f_u$

Type N mortar: $f'_m = 500 + 0.25f_u$

f'_m (psi)	Net area compressive strength of CMU units (psi)	
	Type M or S mortar	Type N mortar
1,750	----	2,000
2,000	**2,000**	2,650
2,250	2,600	3,400
2,500	3,250	4,350
2,750	3,900	----
3,000	4,500	----

Type M or S mortar: $f'_m = 1200 + 0.4f_u$

Type N mortar: $f'_m = 1150 + 0.32f_u$

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Constitutive Properties

Property	TMS 402 reference	Clay Masonry	Concrete Masonry
Modulus of Elasticity, E_m	Table 4.2.2	$700f'_m$	$900f'_m$
Shear Modulus, G	Table 4.2.2	$0.4E_m$ $(\nu = 0.25)$	

Typical Values

Property		Clay Masonry	Concrete Masonry
Unit strength		$8250\ psi$	$\mathbf{2000\ psi}$
Type N mortar	f'_m	$2500\ psi$	$1750\ psi$
	E_m	$1.75x10^6\ psi$	$1.58x10^6\ psi$
Type M or S mortar	f'_m	$3000\ psi$	$\mathbf{2000\ psi}$
	E_m	$2.10x10^6\ psi$	$\mathbf{1.80x10^6\ psi}$

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Flexural Design





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Design Assumptions

1. Member is straight prismatic section (not in code, but an assumption for our analysis)
2. Plane sections remain plane
3. All masonry in tension is neglected
4. Perfect bond between steel and grout
5. Maximum useable compression strain of masonry
   A. clay masonry: ε_{mu} = 0.0035
   B. concrete masonry: ε_{mu} = 0.0025
6. Equivalent rectangular stress block
   A. Masonry stress = $0.8f'_m$
   B. Masonry stress acts over a = $0.8c$

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Comparison to ACI 318

Parameter	TMS 402	ACI 318
Maximum useable compression strain, ε_{mu}	CMU: 0.0025 Clay masonry: 0.0035	0.003
Compressive stress	$0.80f'_m$	$0.85f'_c$
Depth of stress block, a	$a = 0.8c$	$a = 0.85c$ Less for higher f'_c
Strength reduction factor, ϕ	0.90	0.90 Less for higher compression

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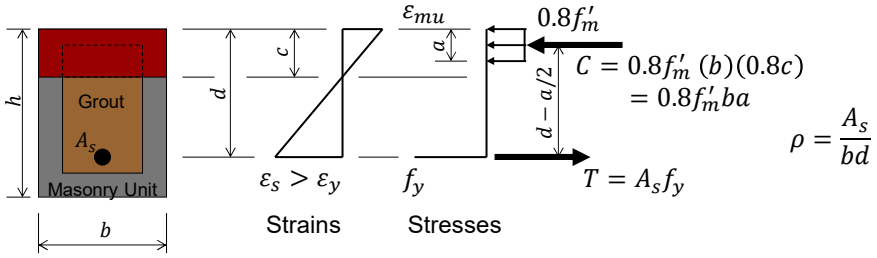
Flexural Members - Strength Design



$$\rho = \frac{A_s}{bd}$$

$$T = C$$

$$A_s f_y = 0.8f'_m(b)(a)$$

$$a = \frac{A_s f_y}{0.8f'_m b}$$

$$M_n = A_s f_y \left(d - \frac{1}{2}\frac{A_s f_y}{0.8f'_m b} \right)$$

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Beams – Strength Design Procedure

1. Determine material properties $(f_y,\ f'_m)$
2. Choose beam dimensions
   A. Thickness: 8 in., 12 in.
   B. Depth: if possible, choose so no shear reinforcement is required

$$d \geq \frac{V_u}{1.8b\sqrt{f'_m}}$$

3. Determine a, depth of compressive stress block

$$a = d - \sqrt{d^2 - \frac{2M_n}{0.8f'_m b}} = d - \sqrt{d^2 - \frac{2M_u}{0.8\phi f'_m b}}$$

4. Solve for $A_{s,reqd}$

$$A_{s,reqd} = \frac{0.8f'_m ba}{f_y}$$

Beams: Minimum Reinforcement

Minimum reinforcement: (9.3.4.2.2.2, 9.3.4.2.2.3)

- $M_n \geq 1.3M_{cr}$
  - Modulus of rupture: Table 9.1.9.2
  - $M_{cr} = f_r \frac{bh^2}{6}$
- or $A_s \geq (4/3)A_{s,reqd}$

Design Tip:
M_n often not calc
$M_u \geq 1.17M_{cr}$

Flexural Tension Parallel to Bed Joint	Mortar Type			
	PCL or mortar cement		Masonry Cement	
	M or S	N	M or S	N
Running bond; hollow units; fully grouted	267	200	160	100
Not laid in running bond; continuous grout section parallel to bed joints	335	335	335	335

Beams –Maximum Reinforcement

Maximum reinforcement: (9.3.3.2)
Reinforcement shall NOT exceed area required to maintain equilibrium under a strain gradient of ε_{mu} in masonry and $\alpha\varepsilon_y$ = 1.5ε_y in reinforcement.

$$\rho_{max} = \frac{0.8(0.8)f'_m}{f_y}\left(\frac{\varepsilon_{mu}}{\varepsilon_{mu} + \alpha\varepsilon_y}\right)$$

Steel Ratio	Grade 60 steel	
	Clay	CMU
ρ_{max}	$0.00565f'_m$ $0.843\rho_{bal}$	$0.00476f'_m$ $0.815\rho_{bal}$
f_y = 60 ksi; f'_m = 2 ksi	0.00113	**0.00952**
f_y = 60 ksi; f'_m = 3 ksi	**0.0169**	0.0144

f'_m in ksi

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Shear - Strength Design (9.3.4.1.2)

$$V_n = (V_{nm} + V_{ns})\gamma_g$$

$$V_{nm} = \left[4 - 1.75\left(\frac{M_u}{V_u d_v}\right)\right]A_{nv}\sqrt{f'_m}$$

$$V_{ns} = 0.5\left(\frac{A_v}{s}\right)f_y d_v$$

- γ_g = partially grouted shear wall factor (γ_g = 1.0 for beams)
- d_v = actual depth of masonry
- A_{nv} = net shear area = bd_v
  - **Many designers use d instead of d_v for beams**
- $M_u/(V_u d_v)$ need not be taken > 1.0
- ϕ= 0.8
- Maximum V_n
  - $V_n \le 6A_{nv}\sqrt{f'_m}$ where $\frac{M_u}{V_u d_v} \le 0.25$
  - $V_n \le 4A_{nv}\sqrt{f'_m}$ where $\frac{M_u}{V_u d_v} \ge 0.25$
  - Linearly interpolate between 0.25 and 1.0

Conservative approximation
$M_u/(V_u d_v)$ = 1.0
$V_{nm} = 2.25A_{nv}\sqrt{f'_m}$

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2022 TMS 402

Table 4.3.5: Net Shear Area for Reinforced Masonry Members

Loading Direction / Member Type	Fully Grouted	Partially Grouted
Out-of-Plane / Wall	$A_{nv} = bd$; b = effective compression width (Section 5.1.2)	$A_{nv} = bd$
In-plane / Planar Shear Wall	$A_{nv} = t_{sp} d_v$	$A_{nv} = A_n$; A_n = net cross-sectional area
In-plane / Flanged Shear Wall	$A_{nv} = t_{sp} d_v$	$A_{nv} = A_n$ of segment of wall that lies parallel to the direction of applied shear
Beams	$A_{nv} = t_{sp} d$	$A_{nv} = 2 t_{fs} d$

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Deflections

- Deflection of beam or lintels supporting unreinforced masonry is limited to $L/600$ (5.2.1.4.1)
- Deflections of approximately $L/300$ needed to be visible
- Deflections do not need to be checked when $L \leq 8d$ (5.2.1.4.3)

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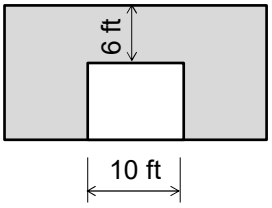
Example: Beam

Given:

- Masonry
  - 8 inch CMU, medium weight (125 pcf)
  - Type S masonry cement mortar
  - f'_m = 2000 psi
- Reinforcement
  - Grade 60 steel
- Geometry
  - 10 ft. opening
  - 6 ft of masonry above opening
- Loads
  - Superimposed dead load of 0.5 kip/ft
  - Live load of 0.5 kip/ft
  - 125 pcf units (81 psf fully grouted; use 45 psf for rest)



Example: Beam

Solution:

Length of bearing: Assume to be 8 in.

Span length: L = 10 ft +2(4 in.) =10.67 ft

Depth to reinforcement: $d \approx h - 4\ \text{in.}$

Approximate weight of beam: $60psf(6ft) = 360\frac{lb}{ft}$

Depth of beam:

$$V_u \sim \frac{w_u L}{2} = \frac{1}{2}\left(1.2\left(0.5\frac{\text{k}}{\text{ft}} + 0.36\frac{\text{k}}{\text{ft}}\right) + 1.6\left(0.5\frac{\text{k}}{\text{ft}}\right)\right)(10.67ft) = 9.8\text{k}$$

$$d \geq \frac{V_u}{1.8b\sqrt{f'_m}} = \frac{9{,}800\text{lb}}{1.8(7.625\text{in.})\sqrt{2000\text{psi}}} = 16\text{in.}$$ Use h = 24 in. deep beam

Example: Beam, Flexure

Factored Load

$$w_u = 1.2D + 1.6L$$
$$= 1.2\left(0.5\,\frac{\text{k}}{\text{ft}} + 0.081\,\frac{\text{k}}{\text{ft}^2}(2\text{ft}) + 0.045\,\frac{\text{k}}{\text{ft}^2}(4\text{ft})\right) + 1.6\left(0.5\,\frac{\text{k}}{\text{ft}}\right) = 1.81\,\frac{\text{k}}{\text{ft}}$$

Factored Moment

$$M_u = \frac{w_u L^2}{8} = \frac{\left(1.81\frac{\text{k}}{\text{ft}}\right)(10.67\text{ft})^2}{8} = 25.8\text{k}\cdot\text{ft}$$

Find a
Depth of equivalent rectangular stress block

$$a = d - \sqrt{d^2 - \frac{2M_n}{0.8f'_m b}}$$
$$= 20\text{in.} - \sqrt{(20\text{in.})^2 - \frac{2\left(\frac{25.8\text{k}\cdot\text{ft}}{0.9}\right)\left(\frac{12\text{in.}}{\text{ft}}\right)}{0.8(2.0\text{ksi})(7.625\text{in.})}} = 1.46\text{in.}$$

Find $A_{s,reqd}$
Req'd area of steel

$$A_{s,reqd} = \frac{0.8f'_m ba}{f_y} = \frac{0.8(2.0\text{ksi})(7.625\text{in.})(1.46\text{in.})}{60\text{ksi}} = 0.29\text{in.}^2$$

Use 1 - #5 (A_s = 0.31 in^2)

Example: Beam, Min and Max Reinforcement

Minimum Reinforcement Check: f_r = 160 psi (parallel to bed joints in running bond; fully grouted)

Section modulus

$$S_n = \frac{bh^2}{6} = \frac{(7.625\text{in.})(24\text{in.})^2}{6} = 732\text{in.}^3$$

Cracking moment

$$M_{cr} = S_n f_r = 732\text{in.}^3\,(160\text{psi})$$
$$= 117.1\text{k}\cdot\text{in.} = 9.76\text{k}\cdot\text{ft}$$

By inspection, $1.17M_{cr} \le M_u = 25.8\text{k}\cdot\text{ft}$

Maximum Reinforcement Check: $\rho_{max} = 0.00952$

$$\rho = \frac{A_s}{bd} = \frac{0.31\text{in.}^2}{(7.625\text{in.})(20\text{in.})} = 0.00203$$

Non-Bearing Walls



https://vancouverconcrete.net/vancouver-block-walls-installation.html

Design based on 1 ft strip

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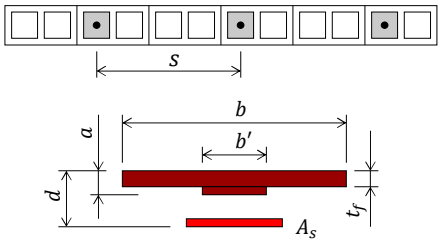
Partially Grouted Walls



b = effective compressive width per bar = min{s, 6t, 72 in.} (5.1.2)
t = nominal thickness

A. Neutral axis in flange:
   a. Almost always the case
   b. Design for solid section
B. Neutral axis in web
   a. Design as a T-beam section
C. Often design based on a 1 ft width

Minimum reinforcement:
No requirements

Maximum reinforcement:
Same requirement as beams

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Partially Grouted Walls: Design Aid

Spacing (inches)	Steel Area in.²/ft			
	#3	#4	#5	#6
8	0.16	0.30	0.46	0.66
16	0.082	0.15	0.23	0.33
24	0.055	0.10	0.16	0.22
32	0.041	0.075	0.12	0.16
40	0.033	0.060	0.093	0.13
48	0.028	0.050	0.078	0.11
56	0.024	0.043	0.066	0.094
64	0.021	0.038	0.058	0.082
72	0.018	0.033	0.052	0.073
80	0.016	0.030	0.046	0.066
88	0.015	0.027	0.042	0.060
96	0.014	0.025	0.039	0.055
104	0.013	0.023	0.036	0.051
112	0.012	0.021	0.033	0.047
120	0.011	0.020	0.031	0.044

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Example - Partially Grouted Wall

Given:

- 8 in. CMU wall
- f'_m = 2000 psi
- 16 ft high
- Grade 60 steel
- Wind load of w_u = 30 psf

Required: Reinforcing (place in center of wall)

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Example - Partially Grouted Wall

Factored Moment M_u

$$M_u = \frac{w_u h^2}{8} = \frac{\left(30\frac{\text{lb}}{\text{ft}^2}\right)\left(12\frac{\text{in.}}{\text{ft}}\right)(16\text{ft})^2}{8} = 11{,}500\,\frac{\text{lb·in.}}{\text{ft}} = 0.960\,\frac{\text{k·ft}}{\text{ft}}$$

Determine d

$$d = \frac{t_{sp}}{2} = \frac{7.625in.}{2} = 3.81in.$$

Depth of stress block, a (Assume solid section)

$$a = d - \sqrt{d^2 - \frac{2M_n}{0.8f'_m b}}$$

$$= 3.81\text{in.} - \sqrt{(3.81\text{in.})^2 - \frac{2\left(\frac{0.960\frac{\text{k·ft}}{\text{ft}}}{0.9}\right)\left(\frac{12\text{in.}}{ft}\right)}{0.8(2.0\text{ksi})\left(\frac{12in.}{\text{ft}}\right)}} = 0.179\text{in.}$$

Required area of steel $A_{s,reqd}$

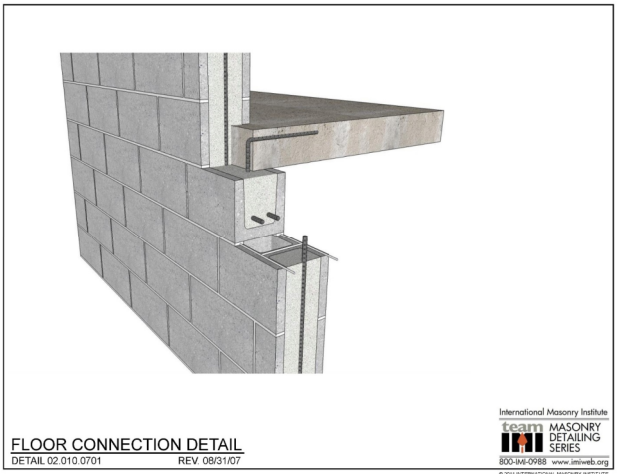
$$A_{s,reqd} = \frac{0.8f'_m ba}{f_y} = \frac{0.8(2.0\text{ksi})\left(12\frac{\text{in.}}{\text{ft}}\right)(0.179\text{in.})}{60\text{ksi}} = 0.057\,\frac{\text{in.}^2}{\text{ft}}$$

Use # 4 @ 40 inches (A_s = 0.060in.²/ft)

$$\rho = \frac{0.060\frac{in.^2}{ft}}{12\frac{in.}{ft}(3.81in.)} = 0.0013$$

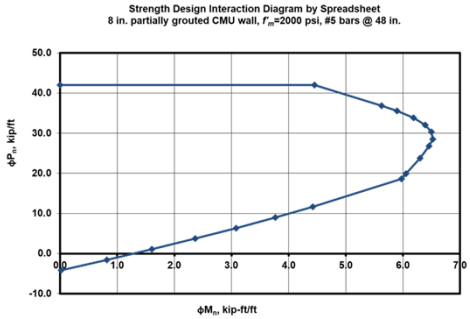
14% of ρ_{max}

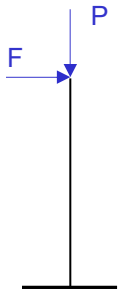
Combined Flexural and Axial Loads: Bearing Walls



Combined Flexure and Axial Load

Design Strength	≥	**Factored Load**
(Interaction Diagram)		(Second-order; P-delta)





P-delta: Slender Wall



Walls: Slenderness Effects

1. **Complementary Moment Design**
   a. In masonry, often called slender wall method
   b. Second-order moment directly added by P-δ
   c. Usually requires iteration
   d. Difficult for hand calculations for other than simple cases
   e. Basis for second-order analysis in computer programs
   f. Historical method used for masonry design
2. **Second-order Analysis**
   a. Added in 2013 TMS 402 Code
   b. Computer analysis
3. **Moment Magnification**
   a. Added in 2013 TMS 402 Code
   b. Very general, but a bit conservative.

Slender Wall 9.3.5.4.2

- Assumes simple support conditions.
- Assumes mid-height moment is maximum moment
- Assumes uniform load over entire height
- Valid only for the following conditions:
  - $\frac{P_u}{A_n} \leq 0.05 f'_m$ No height limit
  - $\frac{P_u}{A_g} \leq 0.20 f'_m$ height limited by $\frac{h}{t} \leq 30$

Moment:

$$M_u = \frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2} + P_u \delta_u$$

$$P_u = P_{uw} + P_{uf}$$

P_{uf} = factored floor load

P_{uw} = factored wall load

Deflection:

$$M_u \leq M_{cr}$$

$$\delta_u = \frac{5 M_u h^2}{48 E_m I_n}$$

$$M_u > M_{cr}$$

$$\delta_u = \frac{5 M_{cr} h^2}{48 E_m I_n} + \frac{5(M_u - M_{cr}) h^2}{48 E_m I_{cr}}$$

Slender Wall Method

Solve simultaneous linear equations:

$M_u > M_{cr}$

$$M_u = \frac{\frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2} + \frac{5M_{cr}P_u h^2}{48E_m}\left(\frac{1}{I_n} - \frac{1}{I_{cr}}\right)}{1 - \frac{5P_u h^2}{48E_m I_{cr}}}$$

$$\delta_u = \frac{\frac{5h^2}{48E_m I_{cr}}\left[\frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2} + M_{cr}\left(\frac{I_{cr}}{I_n} - 1\right)\right]}{1 - \frac{5P_u h^2}{48E_m I_{cr}}}$$

$M_u \le M_{cr}$

$$M_u = \frac{\frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2}}{1 - \frac{5P_u h^2}{48E_m I_n}}$$

$$\delta_u = \frac{\frac{5h^2}{48E_m I_n}\left[\frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2}\right]}{1 - \frac{5P_u h^2}{48E_m I_n}}$$

Walls: Deflections

Cracking Moment: $M_{cr} = \frac{(P_u/A_n + f_r) I_n}{t_{sp}/2}$

Cracked moment of inertia:

$$I_{cr} = n\left(A_s + \frac{P_u}{f_y}\frac{t_{sp}}{2d}\right)(d - c)^2 + \frac{bc^3}{3}$$

Modification for non-centered bars; = 1 for centered bars

Depth to neutral axis: $c = \frac{A_s f_y + P_u}{0.64 f'_m b}$

Cracking Moment

$$M_{cr} = \frac{(P_u/A_n + f_r)I_n}{t_{sp}/2}$$

Grout Spacing (inch)	Modulus of Rupture (psi)			
	Portland cement/Lime or mortar cement		Masonry cement or air entrained PCL	
	Type M or S	Type N	Type M or S	Type N
Fully Grouted	163	158	153	145
16	124	111	102	88
24	110	95	85	69
32	104	88	77	60
40	100	83	71	54
48	97	80	68	50
Ungrouted	84	64	51	31

Walls: Deflections

Deflection Limit $\delta_s \leq 0.007h$

- Calculated using allowable stress load combinations
- Usually D+0.6W or D+0.7E controls

Preliminary Design

Wall thickness: 8 in. up to ≈ 24 ft in height $(h/t = 36)$

Wall thickness	Partial grout	Full grout
6 inch	35 psf	60 psf
8 inch	45 psf	80 psf
12 inch	65 psf	120 psf

Centered reinforcement: $A_{s,reqd} \sim \frac{M_u}{0.8 f_y d} - \frac{P_u}{f_y}$

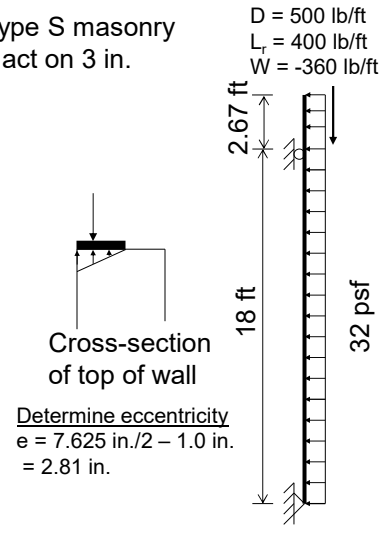
Offset reinforcement: $A_{s,reqd} \sim \frac{M_u}{0.8 f_y d} - \frac{P_u}{2 f_y}$

Example: Bearing Wall

Given: 8 in. CMU wall; Grade 60 steel; Type S masonry cement mortar; f'_m = 2000 psi; roof forces act on 3 in. wide bearing plate at edge of wall.

Required: Reinforcement

Solution:



Cross-section of top of wall

Determine eccentricity
e = 7.625 in./2 – 1.0 in.
= 2.81 in.

Example: Preliminary Design

Estimate reinforcement

$$M_u \sim \frac{wh^2}{8} = \frac{(0.032\text{ksf})(18\text{ft})^2}{8} = 1.30\frac{\text{k-ft}}{\text{ft}} = 15.6\frac{\text{k-in.}}{\text{ft}}$$

Wall weight estimated as 45 psf

$$P_u = 0.9D + W = 0.9\left(500\frac{\text{lb}}{\text{ft}} + 45\text{psf}\left(2.67\text{ft} + \frac{18\text{ft}}{2}\right)\right) - 360\frac{\text{lb}}{\text{ft}} = 562\frac{\text{lb}}{\text{ft}}$$

$$A_{s,reqd} \sim \frac{M_u}{0.8f_y d} - \frac{P_u}{f_y} = \frac{15.6\frac{\text{k-in.}}{\text{ft}}}{0.8(60\text{ksi})(3.81\text{in.})} - \frac{0.562\frac{\text{kip}}{\text{ft}}}{60\text{ksi}} = 0.076\frac{in.^2}{ft}$$

Try #4 @ 32 in.

or #5 @ 48 in.

Wall weight = 38 psf (lightweight weight)

Example: Axial Loads

Summary of Strength Design Load Combination Axial Forces
(wall weight is 38 psf for 48 in. grout spacing)

Load Combination	P_{uf} (kip/ft)	P_{uw} (kip/ft)	P_u (kip/ft)
0.9D+1.0W	0.9(0.5)+1.0(-0.36) = 0.090	0.9(0.038)(2.67+9) = 0.399	0.489
1.2D+1.0W+0.5L_r	1.2(0.5)+1.0(-0.36) +0.5(0.4) = 0.440	1.2(0.038)(2.67+9) = 0.532	0.972

P_{uf} = Factored floor load; just eccentrically applied load

P_{uw} = Factored wall load; includes wall and parapet weight, found at mid-height of wall between supports (9 ft from bottom)

Example: Cracking Moment

Modulus of rupture: use linear interpolation between no grout and full grout

Ungrouted (Type S masonry cement): 51 psi

Fully grouted (Type S masonry cement): 153 psi

$$f_r = 51\text{psi}\left(\frac{5\text{ ungrouted cells}}{6\text{ cells}}\right) + 153\text{psi}\left(\frac{1\text{ grouted cells}}{6\text{ cells}}\right) = 68\text{psi}$$

Cracking moment, M_{cr}:

Commentary allows inclusion of axial load (9.3.5.4.4)

Use minimum axial load (once wall has cracked, it has cracked)

$$M_{cr} = \frac{(P_u/A_n + f_r)I_n}{t_{sp}/2} = \frac{\left(489\frac{\text{lb}}{\text{ft}}/40.7\frac{\text{in.}^2}{\text{ft}} + 68\text{psi}\right)332.0\frac{\text{in.}^4}{\text{ft}}}{7.62\text{in.}/2}$$

$$= 6.97\frac{\text{k}\cdot\text{in.}}{\text{ft}} = 0.581\frac{\text{k}\cdot\text{ft}}{\text{ft}}$$

Wall properties determined from NCMA TEK 14-1B Section Properties of Concrete Masonry Walls



Example: Cracked Moment of Inertia

Modular ratio, n

$$n = \frac{E_s}{E_m} = \frac{29000\text{ksi}}{1800\text{ksi}} = 16.1$$

Depth to neutral axis, c

$$c = \frac{A_s f_y + P_u}{0.64 f'_m b} = \frac{0.0775\frac{\text{in.}^2}{\text{ft}}(60\text{ksi}) + 0.489\frac{\text{k}}{\text{ft}}}{0.64(2\text{ksi})12\frac{\text{in.}}{\text{ft}}} = 0.334\text{in.}$$

Cracked moment of inertia, I_{cr}

$$I_{cr} = n\left(A_s + \frac{P_u}{f_y}\right)(d-c)^2 + \frac{bc^3}{3}$$

$$= 16.1\left(0.0775\frac{\text{in.}^2}{\text{ft}} + \frac{0.0489\frac{\text{k}}{\text{ft}}}{60\text{ksi}}\right)(3.812\text{in.} - 0.334\text{in.})^2 + \frac{12\frac{\text{in.}}{\text{ft}}(0.334\text{in.})^3}{3}$$

$$= 16.8\frac{\text{in.}^4}{\text{ft}}$$

Example: Factored Moment

Find M_u $P_{uf}e_u$ is the moment at the top support of the wall. It includes eccentric axial load and wind load from parapet.

M_{uf} = factored moment at top of wall

w_{up} = factored out-of-plane load on parapet

h_p = height of parapet

$$M_{uf} = P_{uf}e_u - \frac{w_{up}h_p^2}{2} = 0.090\,\frac{\text{k}}{\text{ft}}\left(\frac{2.81}{12}\text{ft}\right) - \frac{0.032\text{ksf}(2.67\text{ft})^2}{2} = -0.093\,\frac{\text{k·ft}}{\text{ft}}$$

Example: Factored Moment

$$M_u = \frac{\frac{w_u h^2}{8} + \frac{M_{uf}}{2} + \frac{5M_{cr}P_u h^2}{48E_m}\left(\frac{1}{I_n} - \frac{1}{I_{cr}}\right)}{1 - \frac{5P_u h^2}{48E_m I_{cr}}}$$

$$= \frac{\frac{0.032\text{ksf}(18\text{ft})^2}{8} + \frac{-0.093\frac{\text{k·ft}}{\text{ft}}}{2} + \frac{5\left(0.581\frac{\text{k·ft}}{\text{ft}}\right)\left(0.489\frac{\text{k}}{\text{ft}}\right)(18\text{ft})^2}{48(1800\text{ksi})}\left(\frac{1}{332\frac{\text{in.}^4}{\text{ft}}} - \frac{1}{16.8\frac{\text{in.}^4}{\text{ft}}}\right)\left(\frac{144\text{in.}^2}{1\text{ft}^2}\right)}{1 - \frac{5\left(0.489\frac{\text{k}}{\text{ft}}\right)(18\text{ft})^2}{48(1800\text{ksi})\left(16.8\frac{\text{in.}^4}{\text{ft}}\right)}\left(\frac{144\text{in.}^2}{1\text{ft}^2}\right)}$$

$$= 1.309\,\frac{\text{k·ft}}{\text{ft}}$$

Whew! We have the factored moment.

Is the (M_u, P_u) combination of $(1.309\,\frac{\text{k·ft}}{\text{ft}}, 0.489\,\frac{\text{k}}{\text{ft}})$ inside the interaction diagram?

Example: Design Strength

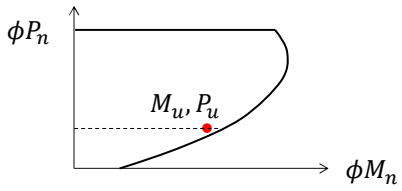
Compare to capacity (interaction diagram)

Depth of stress block, a

$$a = \frac{A_s f_y + P_u/\phi}{0.8 f'_m b} = \frac{0.0775\frac{\text{in.}^2}{\text{ft}} + 0.489\frac{\text{k}}{\text{ft}}/0.9}{0.8(2\text{ksi})\left(12\frac{\text{in.}}{\text{ft}}\right)} = 0.270\text{in.}$$

Design moment, ϕM_n

$$\phi M_n = \phi\left(\frac{P_u}{\phi} + A_s f_y\right)\left(d - \frac{a}{2}\right)$$
$$= 0.9\left(\frac{0.489\frac{\text{k}}{\text{ft}}}{0.9} + 0.0775\frac{\text{in.}^2}{\text{ft}}(60\text{ksi})\right)\left(3.812\text{in.} - \frac{0.270\text{in.}}{2}\right)$$
$$= 17.19\frac{\text{k·in.}}{\text{ft}} = 1.432\frac{\text{k·ft}}{\text{ft}}$$



Finding point on interaction diagram where $\phi P_n = P_u$.

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Example: Load Combinations

Load Combination	M_u (kip-ft/ft)	ϕM_n (kip-ft/ft)	$\frac{M_u}{\phi M_n}$	2nd Order / 1st Order
1.2D+1.6L_r+0.5W	0.799	1.755	0.455	1.074
1.2D+1.0W+0.5L_r	1.416	1.574	0.900	1.097
0.9D+1.0W	1.309	1.432	0.914	1.047

OK

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Example: Deflections

Check Deflections:
A quick check is made using SD Load Combinations

Load Combination	δ_u (in.)
1.2D+1.0W+0.5L_r	1.53
0.9D+1.0W	1.43

$$\delta_u = \frac{M_u - \frac{w_u h^2}{8} - \frac{M_{uf}}{2}}{P_u}$$

Deflection Limit
Section 9.3.5.5

$$\delta_s \le 0.007h = 0.007(18\text{ft})\frac{12\text{in.}}{\text{ft}} = 1.51\text{in.}$$

OK
(close enough)

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Example: Deflections

Check Deflections: Use ASD Load Combinations

Load Combination	D+0.6W	0.6D+0.6W
P_f (k/ft)	0.5+0.6(-0.36) = 0.284	0.6(0.5)+0.6(-0.36) = 0.084
P_w (k/ft)	38(2.67+9) = 0.443	0.6(0.443) = 0.266
P (k/ft)	0.727	0.350
c (in.)	0.350	0.325
I_{cr} (in.^{4}/ft)	17.48	16.46
M_f (k-ft/ft)	-0.002	-0.049
M (k-ft/ft)	0.805	0.767
δ (in.)	0.474	0.426

Deflection Limit: $\delta_s \le 0.007h = 0.007(18\text{ft})\left(12\frac{\text{in.}}{\text{ft}}\right) = 1.51\text{in.}$ **OK**

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Example: Deflections

Deflections, Sample Calculations: **D + 0.6W**
Replace factored loads with service loads

$$\delta = \frac{\frac{5h^2}{48E_m I_{cr}}\left[\frac{wh^2}{8}+\frac{M_f}{2}+M_{cr}\left(\frac{I_{cr}}{I_n}-1\right)\right]}{1-\frac{5Ph^2}{48E_m I_{cr}}}$$

$$= \frac{\frac{5(18\text{ft})^2}{48(1800\text{ksi})\left(17.5\frac{\text{in.}^4}{\text{ft}}\right)}\left[\frac{0.6(0.032\text{ksf})(18\text{ft})^2}{8}+\frac{-0.002\frac{\text{k}\cdot\text{ft}}{\text{ft}}}{2}+0.581\frac{\text{k}\cdot\text{ft}}{\text{ft}}\left(\frac{17.5\frac{\text{in.}^4}{\text{ft}}}{332\frac{\text{in.}^4}{\text{ft}}}-1\right)\right]\frac{144\text{in.}^2}{\text{ft}^2}}{1-\frac{5\left(0.727\frac{\text{k}}{\text{ft}}\right)(18\text{ft})^2}{48(1800\text{ksi})\left(17.5\frac{\text{in.}^4}{\text{ft}}\right)}\frac{144\text{in.}^2}{\text{ft}^2}}$$

$$= 0.0393\text{ft} = 0.474\text{in.}$$

Walls: Maximum Reinforcement

- Strain gradient of ε_{mu} and $\alpha\varepsilon_y$, with α = 1.5 for OOP loading
- P_u determined from $D + 0.75L + 0.525Q_E$

Fully grouted with equal tension and compression reinforcement

$$\rho = \frac{A_s}{bd} = \frac{0.64f'_m\left(\frac{\varepsilon_{mu}}{\varepsilon_{mu}+\alpha\varepsilon_y}\right)-\frac{P_u}{bd}}{f_y - \min\{\varepsilon_{mu}-\frac{d'}{d}(\varepsilon_{mu}+\alpha\varepsilon_y), \varepsilon_y\}E_s}$$

Fully grouted with concentrated tension reinforcement, or partially grouted with neutral axis in face shell

$$\rho = \frac{A_s}{bd} = \frac{0.64f'_m\left(\frac{\varepsilon_{mu}}{\varepsilon_{mu}+\alpha\varepsilon_y}\right)-\frac{P_u}{bd}}{f_y}$$

Partially grouted walls with concentrated tension reinforcement and neutral axis in web

$$\rho = \frac{0.64f'_m\left(\frac{\varepsilon_{mu}}{\varepsilon_{mu}+\alpha\varepsilon_y}\right)\left(\frac{b_w}{b}\right)+0.8f'_m t_{fs}\left(\frac{b-b_w}{bd}\right)-\frac{P_u}{bd}}{f_y}$$

Walls: Maximum Reinforcement

Maximum Axial Load from Load Combination D + 0.75L +0.525Q_E to Meet Maximum Reinforcement Requirements for 8 in. CMU Wall, Centered Grade 60 Reinforcement, f'_m = 2000 psi

Bar Size	Bar spacing					
	8 in.	16 in.	24 in.	32 in.	40 in.	48 in.
No. 4	8.1 k/ft	16.1 k/ft	18.7 k/ft	20.0 k/ft	20.8 k/ft	21.4 k/ft
No. 5	1.5 k/ft	11.1 k/ft	15.4 k/ft	17.6 k/ft	18.8 k/ft	19.7 k/ft
No. 6		5.3 k/ft	11.5 k/ft	14.6 k/ft	16.5 k/ft	17.8 k/ft
No. 7		1.2 k/ft	6.7 k/ft	11.0 k/ft	13.6 k/ft	15.4 k/ft

- For values not listed, a tension force would be required to meet the maximum reinforcement requirements.
- Values listed in green are for $f'_m = 2250\ psi$; require a unit strength of 2600 psi

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Shear Walls



https://www.atcouncil.org/images/Session3_Presentation4_AHMADI.pdf

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Axial and Flexural Strength

- Interaction Diagram
  - Partial Grout: Equivalent Thickness
- Estimate Reinforcement

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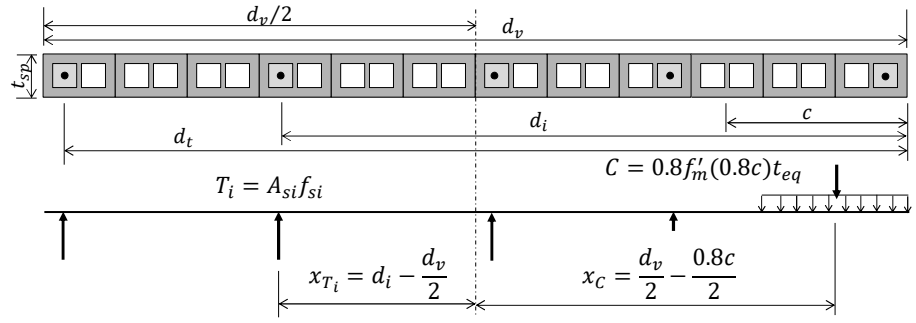
Interaction Diagram



$$\varepsilon_s = \varepsilon_{mu}\frac{d_t - c}{c}$$

$$\varepsilon_{si} = \varepsilon_s\frac{d_i - c}{d_t - c}$$

$$f_{si} = \min\{E_s\varepsilon_{si}, f_y\}$$

$$P_n = C - \sum_{d_i>c} T_i$$

$$M_n = Cx_C + \sum_{d_i>c} T_i x_{Ti}$$

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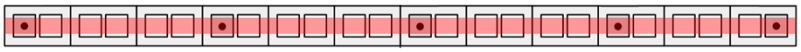
Equivalent Thickness

An equivalent thickness can be used for partially grouted walls

Grout Spacing (in.)	Equivalent Thickness, t_{eq} (in.)	
	8 in. CMU	12 in. CMU
16	5.17	7.28
24	4.28	5.69
32	3.83	4.89
40	3.57	4.41
48	3.39	4.09
72	3.09	3.56
96	2.94	3.30
120	2.86	3.13



Example: Interaction Diagram

Given:

- 10 ft high x 16 ft long 8 in. CMU shear wall
- f'_m = 2000 psi
- #4 Grade 60 steel @ 48 in.

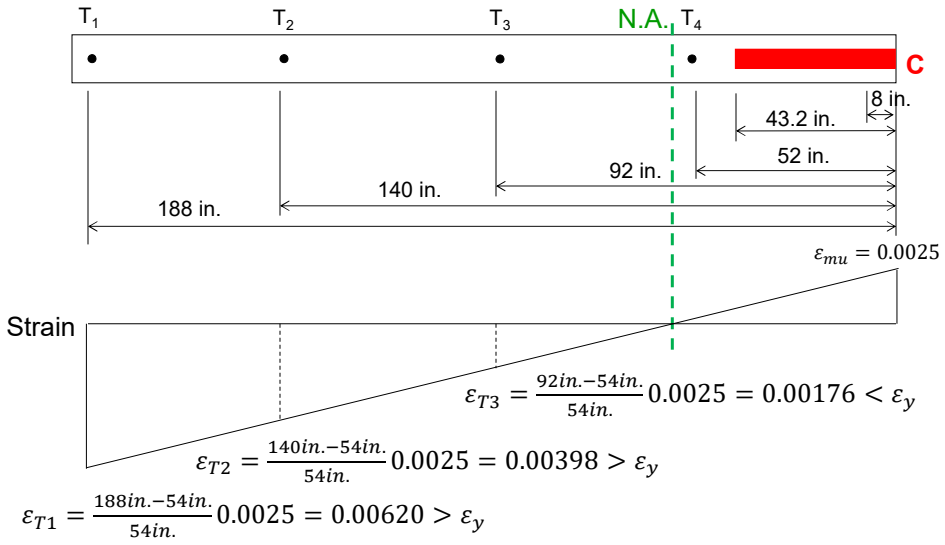
Required: Draw interaction diagram

Solution:

$t_{eq} =$ 3.39 inch

Example: Interaction Diagram

Interaction diagram: Illustrate with c = 54 in., a = 0.8(54) = 43.2 in.



$$\varepsilon_{T3} = \frac{92in.-54in.}{54in.}0.0025 = 0.00176 < \varepsilon_y$$

$$\varepsilon_{T2} = \frac{140in.-54in.}{54in.}0.0025 = 0.00398 > \varepsilon_y$$

$$\varepsilon_{T1} = \frac{188in.-54in.}{54in.}0.0025 = 0.00620 > \varepsilon_y$$

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Example: Interaction Diagram

Masonry force, C

$$C = 0.8f'_m(0.8c)t_{eq} = 0.8(2\text{ksi})(0.8)(54\text{in.})(3.39\text{in}) = 234.3\text{ kip}$$

Masonry arm, x_C

$$x_C = \frac{d_v}{2} - \frac{0.8c}{2} = \frac{192\text{in.}}{2} - \frac{0.8(54\text{in.})}{2} = 74.4\text{in.}$$

Layer	d (in.)	Strain	Stress (ksi)	Force (kip)	Moment Arm (in.)
1	188	0.00620	60	$60(0.2) = 12$	$d_i - \frac{d_v}{2} = 188 - \frac{192}{2} = 92$
2	140	0.00398	60	12	44
3	44	0.00176	$0.00176(29000\text{ksi}) = 51.0\text{ksi}$	10.2	-4

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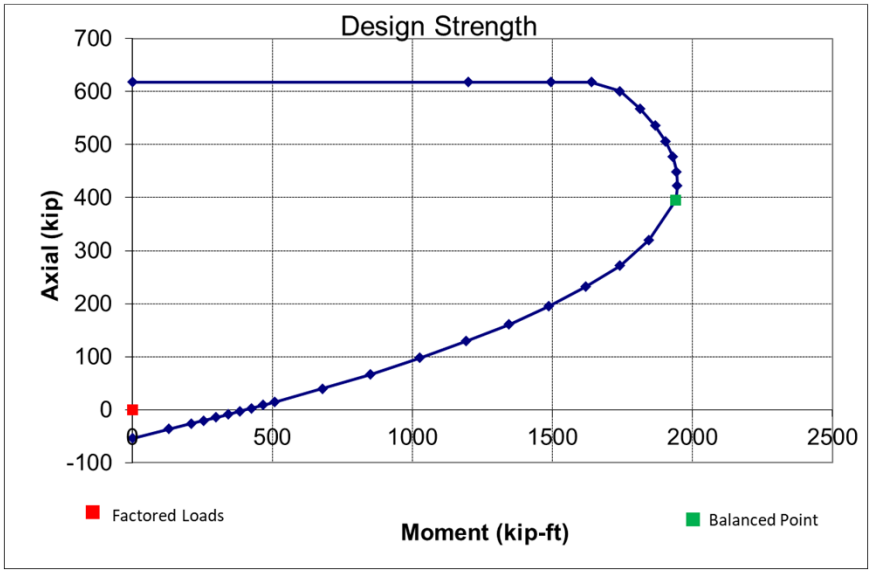
Example: Interaction Diagram

$$\phi P_n = \phi(C - T_1 - T_2 - T_3)$$
$$= 0.9(234.3\text{k} - 12.0\text{k} - 12.0\text{k} - 10.2\text{k}) = 180.1\text{k}$$

Sum moments about middle of wall (8 ft from end) to find ϕM_n

$$\phi M_n = 0.9[234.3\text{k}(74.4in.) + +12.0\text{k}(92in.) + 12.0\text{k}(44in.) + 10.2\text{k}(-4in.)]$$
$$= 17{,}121\text{k} \cdot \text{in.} = 1427\text{k} \cdot \text{ft}$$

Example: Interaction Diagram



Design: Distributed Reinforcement

- Spacing of intermediate reinforcing bars often controlled by out-of-plane loading.
- Following procedure uses a “smeared” reinforcement model to estimate the required reinforcement.
- An interaction diagram is used to check the design.

Approximate Wall Weights

Wall thickness	Partial grout	Full grout
6 inch	35 psf	60 psf
8 inch	45 psf	80 psf
12 inch	65 psf	120 psf

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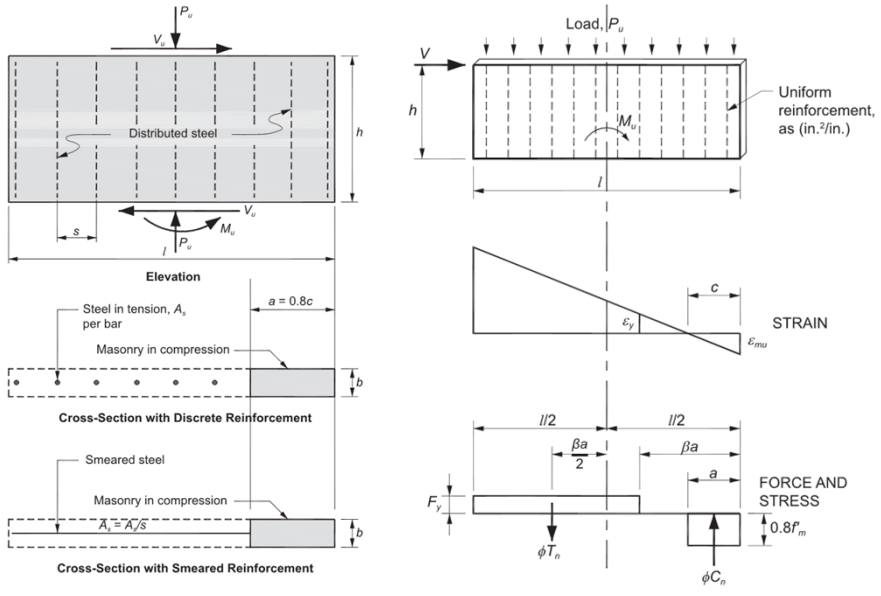
Design: Distributed Reinforcement



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Design: Distributed Reinforcement

Solve quadratic equation for depth of compression block, a:

$$a = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

$$A = (\beta - 1)0.36f'_m t_{sp}$$

$$B = 0.36f'_m t_{sp} d_v - 0.5\beta P_u$$

$$C = -M_u$$

$$\beta = \frac{\varepsilon_y + \varepsilon_{mu}}{0.8\varepsilon_{mu}}$$

For Grade 60 steel:

$\beta = 2.3$ for concrete masonry

$\beta = 2.0$ for clay masonry

Solve for required area of steel per inch of wall length:

$$A^*_{s,req'd} = \frac{0.8f'_m a t_{sp} - P_u/\phi}{f_y(d_v - \beta a)}$$

Method tends to slightly overestimate $A^*_{s,req'd}$, particularly for wider spaced reinforcement.

Shear Strength



Shear Strength (9.3.4.1.2)

$V_n = (V_{nm} + V_{ns})\gamma_g \quad \phi = 0.8$

γ_g = 0.75 for partially grouted shear walls and 1.0 otherwise

$$V_{nm} = \left[4.0 - 1.75\left(\frac{M_u}{V_u d_v}\right)\right] A_{nv}\sqrt{f'_m} + 0.25P_u$$

$$V_{ns} = 0.5\left(\frac{A_v}{s}\right) f_y d_v$$

$M_u/(V_u d_v)$ need not be taken > 1.0
P_u compressive axial load

Maximum Shear:

$V_n \le (6A_{nv}\sqrt{f'_m})\gamma_g \quad \left(\frac{M_u}{V_u d_v}\right) \le 0.25$

$V_n \le (4A_{nv}\sqrt{f'_m})\gamma_g \quad \left(\frac{M_u}{V_u d_v}\right) \ge 1.0$

Interpolate for $0.25 < \left(\frac{M_u}{V_u d_v}\right) < 1.0 \quad V_n \le \left(\frac{4}{3}\left(5 - 2\frac{M_u}{V_u d_v}\right) A_{nv}\sqrt{f'_m}\right)\gamma_g$

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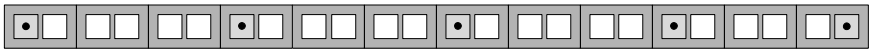
Example: Shear

Given: 10 ft high x 16 ft long 8 in. CMU shear wall; Grade 60 steel, f'_m =2000 psi; #4 at 48in.; superimposed dead load of 1 kip/ft. In-plane seismic load of 50 kips.



Required: Design for shear

Solution: Net area is shown below



$A_{nv} = 2(1.25\text{in.})(192\text{in.}) + 5(8\text{in.})(7.625\text{in.} - 2.5\text{in.}) = 685\text{in.}^2$

Using equivalent thickness, $A_{nv} = 3.39\text{in.}(192\text{in.}) = 651\text{in.}^2$

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Example: Shear

Shear Span: $\frac{M_u}{V_u d_v} = \frac{V_u h}{V_u d_v} = \frac{h}{d} = \frac{120\text{in.}}{192\text{in.}} = 0.625$

Max Shear: $\phi V_{n,max} = \phi\left[\frac{4}{3}\left(5 - 2\frac{M_u}{V_u d_v}\right) A_{nv}\sqrt{f'_m}\right]\gamma_g$

$= 0.8\left[\frac{4}{3}\left(5 - 2(0.625)\right)(685\text{in.}^2)\sqrt{2000\text{psi}}\right]0.75 = 91.9\text{kip}$

OK

Masonry Shear: $\phi V_{nm} = \phi\left[\left(4 - 1.75\left(\frac{M}{V d_v}\right)\right) A_{nv}\sqrt{f'_m} + 0.25 P_u\right]\gamma_g$

$= 0.8\left[\left(4 - 1.75(0.625)\right)(685\text{in.}^2)\sqrt{2000\text{psi}} + 0.25(18600\text{lb})\right]0.75$

$= 56.2\text{kip}$

OK

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Shear Friction Provisions

$M_u/(V_u d_v) \le 0.5 \qquad V_{nf} = \mu\left(A_{sp} f_y + P_u\right)$

$M_u/(V_u d_v) \ge 1.0 \qquad V_{nf} = 0.42 f'_m A_{nc}$

Linear interpolation for intermediate values

A_{nc} = area of masonry in compression at nominal moment capacity

A_{sp} = reinforcement within net shear area

Coefficient of friction

- μ = 1.0 for masonry on concrete with unfinished surface, or concrete with a surface that has been intentionally roughened
  - UBC (1997) required concrete abutting structural masonry to be roughened to a full amplitude of 1/16 inch.
- μ = 0.70 for all other conditions

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Shear Friction Provisions: Approximations for $M_u/V_u d_v \geq 1$

1. Estimate A_{nc}. Determine c as:
   $c = \frac{A_s f_y + P_u/\phi}{0.64 f'_m t_{sp}}$
   A very quick approximation is that any reinforcement greater than $2c$ has yielded.
   This is exact value of c if all tension steel has yielded.

2. Estimate the shear friction strength as
   $V_{nf} = 0.65(0.6 A_{sp} f_y + P_u)$

2022: $V_{nf} = 0.65(0.75 A_{sp} f_y + P_u)$

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Example: Shear Friction Design

Given: 10 ft high x 16 ft long 8 in. CMU shear wall; Grade 60 steel, Type S mortar; f'_m = 2000 psi; superimposed dead load of 1 kip/ft. In-plane seismic load of 50 kips.

Required: Check shear friction

Solution:

- Assume concrete is unfinished ($\mu = 1.0$)
- Flexural reinforcement was 5 - #4 bars; $A_{sp} = 5(0.20\text{in.}^2) = 1.00\text{in.}^2$
- $P_u = 18.6\text{k}$
- $M_u/(V_u d_v) = 0.625$
- $A_{nv} = 685\text{in.}^2$
- $t_{eq} = 3.39\text{in.}$

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Example: Shear Friction Design

$\frac{M_u}{V_u d_v} \le 0.5$ $\quad V_{nf} = \mu\left(A_{sp} f_y + P_u\right) = 1.0\left((1.00\text{in.}^2)60\text{ksi} + 18.6\text{k}\right) = 78.6\text{k}$

$\frac{M_u}{V_u d_v} \ge 1.0$ $\quad V_{nf} = 0.42 f'_m A_{nc} = 0.42(2\text{ksi})(3.39\text{in.})(15.8\text{in.}) = 45.0\text{k}$

c = 15.8 in. from interaction diagram where $\phi P_n = P_u = 18.6\text{k}$

Interpolate $\quad V_{nf} = 70.2\text{k} \quad \phi V_{nf} = 0.8(70.2\text{k}) = 56.2\text{k}$ **OK**

$$y_2 = \frac{(x_2 - x_1)(y_3 - y_1)}{(x_3 - x_1)} + y_1 = \frac{(0.625 - 0.5)(45.0\text{k} - 78.6\text{k})}{(1.0 - 0.5)} + 78.6\text{k} = 70.2\text{k}$$

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Example: Shear Friction Design

1. Estimate A_{nc}. Assume 4 bars have yielded Determine c as:

$$c = \frac{A_s f_y + P_u/\phi}{0.64 f'_m t_{sp}} = \frac{4(0.20\text{in.}^2)60\text{ksi} + 18.6\text{k}/0.9}{0.64(2\text{ksi})(3.39\text{in.})} = 15.8\text{in.}$$

This is same value as from interaction diagram since four bars are in tension and all have yielded.

2. Estimate the shear friction strength using the interpolation formula

$$V_{nf} = \left(1.61 - 1.22\frac{M_u}{V_u d_v}\right) A_{sp} f_y + \left(1.35 - 0.70\frac{M_u}{V_u d_v}\right) P_u$$
$$= (1.61 - 1.22(0.625))(1.00\text{in.}^2)60\text{ksi} + (1.35 - 0.70(0.625))18.6\text{k}$$
$$= 67.8\text{k}$$
$$\phi V_{nf} = 0.8(67.8\text{k}) = 54.2\text{kip}$$

OK

Using 2022 equation: $\phi V_{nf} = 55.4\text{kip}$

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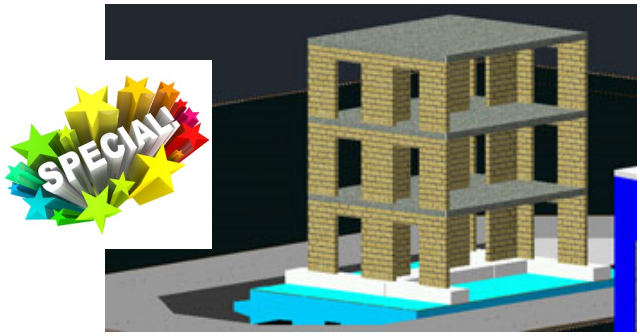
Special Reinforced Shear Walls



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Special Reinforced Shear Walls: Summary

- Prescriptive Reinforcement Requirements (7.3.2.6)
  - 0.0007 in each direction
  - 0.002 total
- Spacing Requirements (7.3.2.6)
  - one-third length of wall
  - one-third height of wall
  - 48 in. for running bond; 24 in. not laid in running bond
- Shear Capacity Design (Section 7.3.2.6.1.2)
  - $\phi V_n \geq$ shear corresponding to $1.25M_n$.
  - V_n need not exceed $2.5V_u$
  - Only applies to shear strength; do not need to increase V_u for $M_u/V_u d_v$ ratio or for shear friction strength
- Maximum Reinforcement Requirements (9.3.3.5; 9.3.6.5)

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Special Walls: Prescriptive Reinforcement

Reinforce-ment Ratio	8 in. CMU wall		12 in. CMU wall	
	A_s (in.^{2}/ft)	Possibilities	A_s (in.^{2}/ft)	Possibilities
0.0007	0.064	#4@32 #5@~~56~~ 48 Max spacing 48	0.098	#4@24 #5@32 #6@48
0.0010	0.092	#4@24 #5@40 #6@~~56~~ 48	0.140	#4@16 #5@24 #6@32 #7@48
0.0013	0.119	#4@16 #5@32 #6@40	0.181	#4@8 #5@16 #6@24 #7@40

Use specified dimensions, e.g. 7.625 in. for 8 in. CMU walls.

Special Walls: Shear Capacity

Minimum shear strength (7.3.2.6.1.1):

- Design shear strength, ϕV_n, greater than shear corresponding to 1.25 times nominal flexural strength, M_n
  - Have to check all load combinations
  - Any change in wall changes M_n
- Except V_n need not be greater than $2.5V_u$.

Normal design:

- ϕV_n has to be greater than V_u
- Thus, V_n has to be greater than V_u/ϕ = V_u/0.8 = $1.25V_u$
- This requirement doubles the shear

Maximum reinforcement

- Methods to ensure ductility
  - Maximum reinforcement provisions
  - ~~Provide boundary elements~~
  - Demonstrate boundary elements aren't required
- Suggested order (easiest to hardest)
  - Screening checks (TMS 9.3.6.6.1)
  - Compression stress check (TMS 9.3.6.6.4)
  - Else, ρ_{max} (TMS 9.3.3.2)

Maximum Reinforcement: Screening Check

Boundary element not required if:

- Axial Load

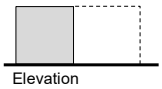
  $P_u \leq 0.10 A_g f'_m$ for geometrically symmetrical sections

  $P_u \leq 0.05 A_g f'_m$ for geometrically **<u>un</u>**symmetrical sections

Recommend using net area for partially grouted construction

- And either

  $\frac{M_u}{V_u d_v} \leq 1.0$



Or

$\frac{M_u}{V_u d_v} \leq 3.0$ and $V_u \leq 3 A_{nv} \sqrt{f'_m}$ $\left(V_n \leq 3.75 A_{nv} \sqrt{f'_m}\right)$



Maximum Reinforcement: Compression Stress Check

Boundary element not required if:

$$\frac{P_u}{A_g} + \frac{M_u}{S_g} < 0.2f'_m$$

Recommend using net section properties for partially grouted construction

- Note: assumes linear elastic behavior and gross (uncracked) section properties
- P_u, M_u from strength level load cases

Maximum Reinforcement (9.3.3.2)

A_s ≤ area required to maintain axial equilibrium under:

- Strain gradient of:
  - ε_{mu} in masonry
  - $\alpha\varepsilon_y$ in reinforcement
- Axial forces from
  - $D + 0.75L + 0.525Q_E$
- Compression reinforcement, with or without lateral restraining reinforcement, can be included.

Shear Wall Type	Yield Strain Multiplier, α	
	$\frac{M_u}{V_u d_v} < 1$	$\frac{M_u}{V_u d_v} \geq 1$
Ordinary	1.5	1.5
Intermediate		3.0
Special		4.0

Maximum Reinforcement: Commentary Equations

- Uniformly distributed, max reinforcement per unit length:

$$\frac{A_s}{d_v} = \frac{0.64 f'_m t_{sp} \left(\frac{\varepsilon_{mu}}{\varepsilon_{mu} + \alpha\varepsilon_y}\right) - \frac{P}{d_v}}{f_y \left(\frac{\alpha\varepsilon_y - \varepsilon_{mu}}{\varepsilon_{mu} + \alpha\varepsilon_y}\right)}$$

- Concentrated at ends and symmetric, ρ_{max} is:

$$\frac{A_s}{t_{sp} d} = \frac{0.64 f'_m \left(\frac{\varepsilon_{mu}}{\varepsilon_{mu} + \alpha\varepsilon_y}\right) - \frac{P}{t_{sp} d}}{f_{y-min}\left(\varepsilon_{mu} - \frac{d'}{d}\left(\varepsilon_{mu} + \alpha\varepsilon_y\right), \varepsilon_y\right) E_s}$$

- P is from load combination D + 0.75L + 0.525Q_E
- Substitute t_{eq} for t_{sp} for partially grouted walls

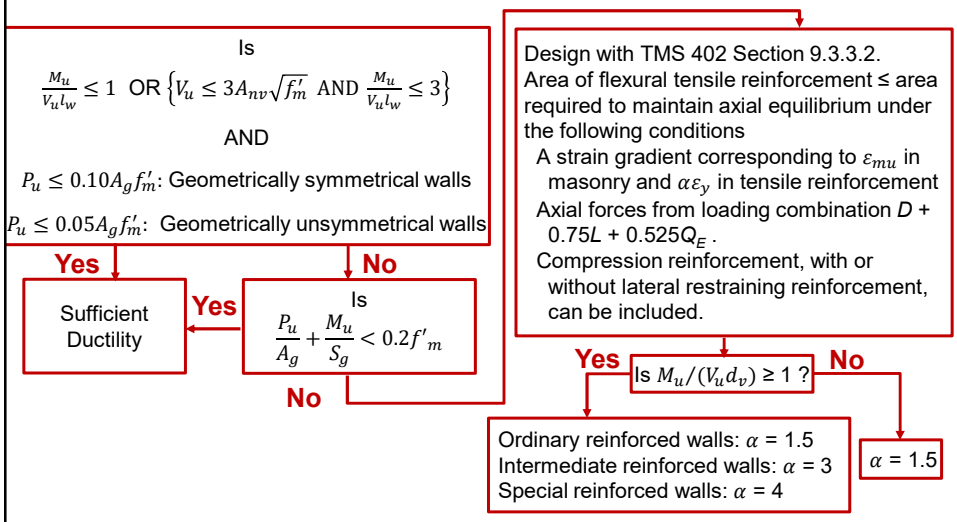
Maximum Reinforcement: Axial Load

- Determine greatest neutral axis depth for which strain limits can be met:

α	c/d_t, CMU	c/d_t, Clay
1.5	0.446	0.530
3	0.287	0.360
4	0.232	0.297

- Solve for P_n for that neutral axis location, using steel in compression.
- If $P_n \geq P$ from D + 0.75L + 0.525Q_E then OK

Maximum Reinforcement: Summary



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Thank you

Richard Bennett
rmbennett@utk.edu

Introduction to Masonry Design

- Seminar Notes
  - Introduction to Masonry Design
- Excel Files
  - Reinforced Beam Analysis and Design
  - Interation Diagram: Partial Grout Out-of-Plane
  - Slender Wall Design
  - Interaction Diagram: Pilaster
  - Interation Diagram: Shear Wall
  - Splice Length
  - Anchor Bolt Design
- Detailed Notes (not covered during seminar)
  - Clay Masonry
  - Concrete Masonry
  - Mortar and Grout
  - Prism Strength, Reinforcement, Construction Practices
  - Masonry properties
  - Flexure Design: Non-bearing walls and lintels
  - Axial and Flexure: Bearing walls, pilasters, columns
  - Shear Walls, including special reinforced walls
  - Anchor Bolts
  - Allowable Stress Design

https://efcms.engr.utk.edu/ce576-2021-06/utah/

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